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Decoupled geomorphic and sedimentary response of Po River and its Alpine tributaries during the last glacial/post-glacial episode

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ABSTRACT

The complex geomorphic and sedimentary evolution of the central Po Plain (northern Italy) during the last 30 ky was reconstructed through the integration of stratigraphic, geomorphological, geochemical and radiocarbon data. A key element of the Late Pleistocene stratigraphy is a 20 km-wide channel-belt sand body, with its top at a depth of ~13 m, fed by the Po River. Whereas the southern boundary of the Po fluvial channel belt coincides with a sharp lithological contact with floodplain muds, its northern boundary is an erosional (sand-on-sand) surface that was traced tentatively in the subsurface with the aid of sediment provenance (Po versus Alpine) proxies and radiocarbon data. Stratigraphic and geomorphological features testify to a decoupled sedimentary and geomorphic response of the Alpine and Po River systems to climate change in the last 30 ky. Contemporaneous Po River incision and Alpine rivers aggradation occurred at the onset of the Last Glacial Maximum (LGM). In contrast, Po River aggradation and Alpine rivers entrenchment took place during early deglaciation. The Holocene stratigraphy records the overall aggradation and northward migration of the Po River, with the consequent erosion of distal Alpine LGM deposits and formation of a fluvial scarp parallel to the Po River course. Late Pleistocene and Holocene climate change influenced river dynamics controlling (i) the balance between sediment supply and water discharge, through glacier and vegetation dynamics, and (ii) the rate of sea-level fall/rise. Apennine, Alpine and Po river systems responded in distinct ways to climate forcing due to the influence of local factors. Lithology, drainage area and mean elevation of river catchments, as well as river and valley gradients, determined the type of sedimentary response (e.g., aggradation versus degradation). This study shows that a combined geomorphic and stratigraphic approach focusing on the geometric relations between exposed and buried features can provide valuable information about the evolution of a fluvial system and its controlling factors.

1. Introduction

The Po Plain in northern Italy is the foreland of two fold-and-thrust belts: the Alps in the north, and the Apennines to the south. These mountain chains developed due to the convergence between Africa and Eurasia, which took place in the Cretaceous (Carminati and Doglioni, 2012, and references therein). In recent decades, a wealth of research has outlined the sedimentary evolution of the Po Basin throughout the Pliocene and the Quaternary. The Po Basin was investigated at different temporal and spatial scales using different methodologies, including seismic-line interpretation (Pieri and Groppi, 1981), core and well-log correlation (Regione Emilia Romagna and Eni-Agip, 1998; Regione Lombardia and Eni divisione Agip, 2002; Amorosi et al., 2004, 2008), geomorphological mapping (Castiglioni et al., 1999; Burrato et al., 2003; Castaldini et al., 2003; Fontana et al., 2014), and geoarcheological surveys (Cremaschi et al., 2006; Bruno et al., 2013; Cremonini et al., 2013). The peculiar geodynamic setting of the Po Plain makes this area a case study of worldwide interest along with other alluvial and coastal systems such as the Rhine-Meuse (Berendsen and Stouthamer, 2000; Busschers et al., 2007), the Texas Gulf Coast (Blum et al., 1994; Blum and Aslan, 2006), the Echigo Plain in Japan (Tanabe et al., 2013), and several other sites along the European Atlantic coastline (Allen and Posamentier, 1993; Chaumillon et al., 2008; Vis and Kasse, 2009). The Po Plain is well suited to the investigation of the sedimentary response of an alluvial system to late Quaternary climate change. Indeed, glacial/interglacial cycles determined glacier advance and retreat in the Alps (Bini and Zuccoli, 2004; Ravazzi et al., 2012a, 2014; Monegato et al., 2017), inducing important variations in sediment production and flux to the basin (Amorosi et al., 2008; Garzanti et al., 2011). The Late Pleistocene-Holocene stratigraphy was extensively investigated in the area south of the Po River (Amorosi et al., 2015, 2017a, 2017b; Bruno et al., 2015, 2017a; Campo et al., 2016),

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whereas only geomorphological studies have been carried out north of the Po River (Fontana et al., 2014). In this latter area, locally named *Lombardian Plain*, the three-dimensional geometry and facies characteristics of Late Pleistocene-Holocene deposits are poorly known and stratigraphic studies have been restricted to relatively small areas (Ravazzi et al., 2012b, 2013). Regional studies have focused on longer time intervals (Amorosi et al., 2008; Garzanti et al., 2011; GeoMol Team, 2015). The result is a fragmentary picture, where different portions of the basin are not linked in a source-to-sink continuum. In particular, the contribution of Alpine sources to the late Quaternary stratigraphy of the Po Plain has not yet been documented. This is of particular interest to assess the response of fluvial systems draining glaciated mountain basins to high-magnitude climate change.

This work aims to examine the sedimentary response to climate and sea-level variations of an alluvial system developed between two active orogens in the last 30,000 yr. To accomplish this, we selected a ~2200 km^2-wide area in the central Po Plain and carried out stratigraphic correlations along four transects traced from the Apennine margin to the southernmost portion of the Alps. Five cores were used for detailed sedimentological and geochemical characterization of material supplied by the Po River and its Alpine tributaries. Stratigraphic relationships between sediment bodies fed by Po and Alpine sources were used to unravel (i) the mechanisms of interaction and sediment transfer between the trunk river and its tributaries, and (ii) the type of sedimentary response (aggradation vs. degradation) of the fluvial system to external forcing (climate change, sea-level oscillations) under the influence of local controlling factors (river catchment lithology and morphology, river and valley gradients, local tectonics).

2. Geological setting

2.1. Structural setting

The Po Plain is bounded by the southern Alps and the northern Apennines, two mountain chains showing opposite vergence (Fig. 1). The southern portion of the Alps consists of a set of thin-skinned, south-verging thrust sheets (Castellarin and Vai, 1986; Castellarin et al., 1992). The most external thrusts are arranged in a single arc buried beneath the Po Plain, between Milan and Garda Lake (Fig. 1).

The northern Apennines are a post-collisional thrust belt mainly developed during the Neogene and Quaternary (Malinverno and Ryan, 1986; Royden et al., 1987; Dewey et al., 1989; Basili and Barba, 2007). The most external Apenninic front is also buried beneath the Po Plain and is composed of three arcs of north-verging thrusts and related folds (Fig. 1). Several earthquakes of low to medium intensity testify to the recent tectonic activity of both buried fronts (Iside Working Group, 2010; Rovida et al., 2011). Fault plane solutions of major instrumental earthquakes show prevailing compressional mechanisms (Pondrelli et al., 2012; Scognamiglio et al., 2012), in agreement with modern GPS measurements, which indicate shortening rates of 1–3 mm/yr across the Po Basin (Devoti et al., 2011).

2.2. Surface geology of the Po River system

The Alps and the Apennines differ in elevation and composition of the exposed rocks. The Alps, with peaks reaching over 4000 m, are characterized to the west and north by extensive outcrops of Mesozoic ultramafic rocks belonging to the Pennine units (Fig. 1). Mesozoic carbonate and dolostone rocks (South-Alpine units in Fig. 1) crop out extensively in the south. The northern Apennines, with highest peaks of about 2100 m, are mainly composed of tectonically deformed clays of Cretaceous age (Ligurian units, Codegone et al., 2012; Carlini et al., 2013) and Tertiary turbidites (Marnoso-arenacea formation, Ricci Lucchi, 1986; Tinterri and Tagliaferri, 2015). Ultramafic rocks also crop out in the northern Apennines, but are of limited extent. The Po River originates in the western Alps and flows across the Po Plain from west to east for 652 km (Fig. 1).

Pleistocene and Holocene strata are exposed in the Po Plain. Late Pleistocene fluvioglacial deposits crop out extensively north of the Po River (Cremaschi, 1987; Castiglioni, 2001). These units are shaped in large (300–3000 km^2) alluvial fans, 30–70 km in length (Fontana et al., 2014). Most of the alluvial fans are characterized by steep

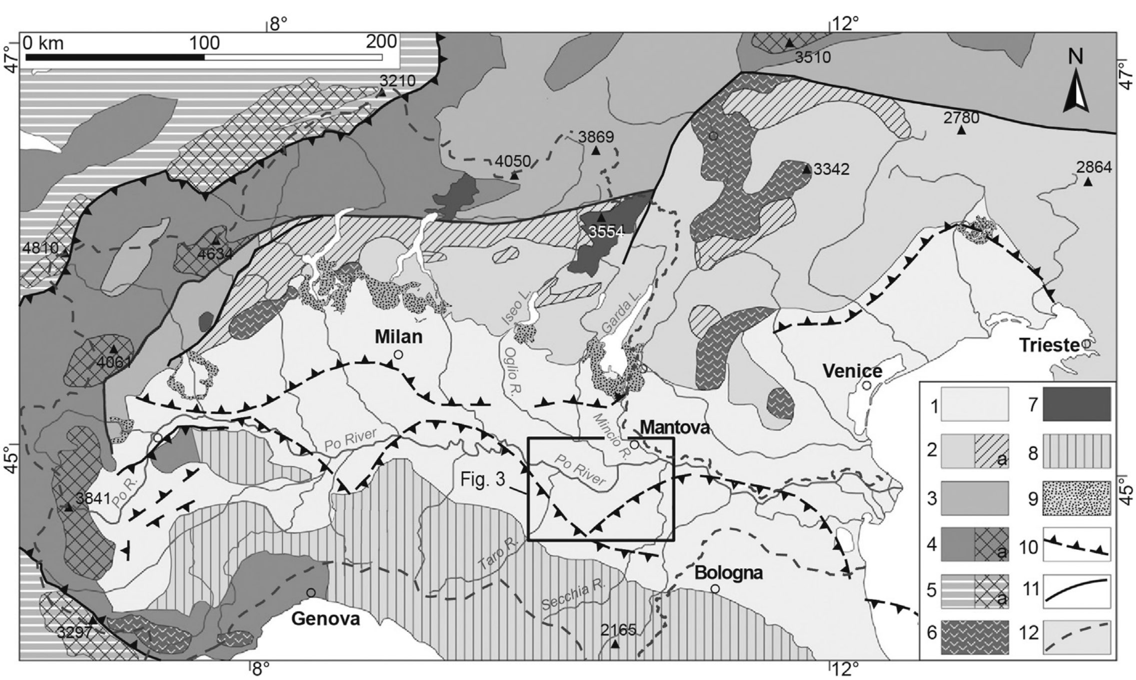

Fig. 1. Geological and structural sketch of northern Italy (modified after Fontana et al., 2014), with location of the study area and of the cross section of Fig. 3. Legend: (1) Plio-Quaternary alluvial and coastal deposits, (2) South-Alpine and Dinaric units, (2a) metamorphic units, (3) Australpine units, (4) Pennine unit, (4a) internal massifs, (5) Helvetic units, (5a) external massifs, (6) volcanic rocks, (7) plutonic rocks, (8) Apennine units, (9) moraine amphitheaters of South-Alpine glaciers, (10) main reverse fault, (11) main fault, (12) boundary of Po River catchment.

(mean gradient of 3–7‰, Castiglioni, 1997; Guzzetti et al., 1997), gravelly piedmont sectors and finer-grained distal portions, with gradients <1‰ (Fig. 2). At the transition from gravel to finer-grained sediments, a dense network of minor groundwater-fed river courses originates from a continuous spring line (Fontana et al., 2014). Extensive swamps, almost completely reclaimed in the last centuries, characterized the spring belt in the past. The major Alpine rivers now flow within single valleys incised into Late Pleistocene deposits (Castiglioni, 1997).

Holocene alluvial deposits are exposed extensively south of the Po River and in the eastern Po Plain. In these areas, ribbon-shaped fluvial ridges, in many cases elevated several meters above the adjacent floodplain, are associated with modern river courses and with abandoned fluvial channels (Fig. 2a).

The study area is located in the central Po Plain and can be subdivided in two sectors (Fig. 3). The northern region is part of the *Lombardian Plain* and is fed by two main Alpine rivers, from west to east, the Oglio and Mincio rivers, flowing from the Iseo and Garda lakes, respectively. These lakes formed at the mouth of Alpine valleys within wide moraine amphitheaters (Figs. 1 and 2a) mostly dated to the LGM (Carraro and Giardino, 2004; Castiglioni, 2004; Monegato et al., 2017). Radiocarbon and pollen data indicate that the Iseo and Garda amphitheaters were largely deglaciated around 18–17 cal ky BP

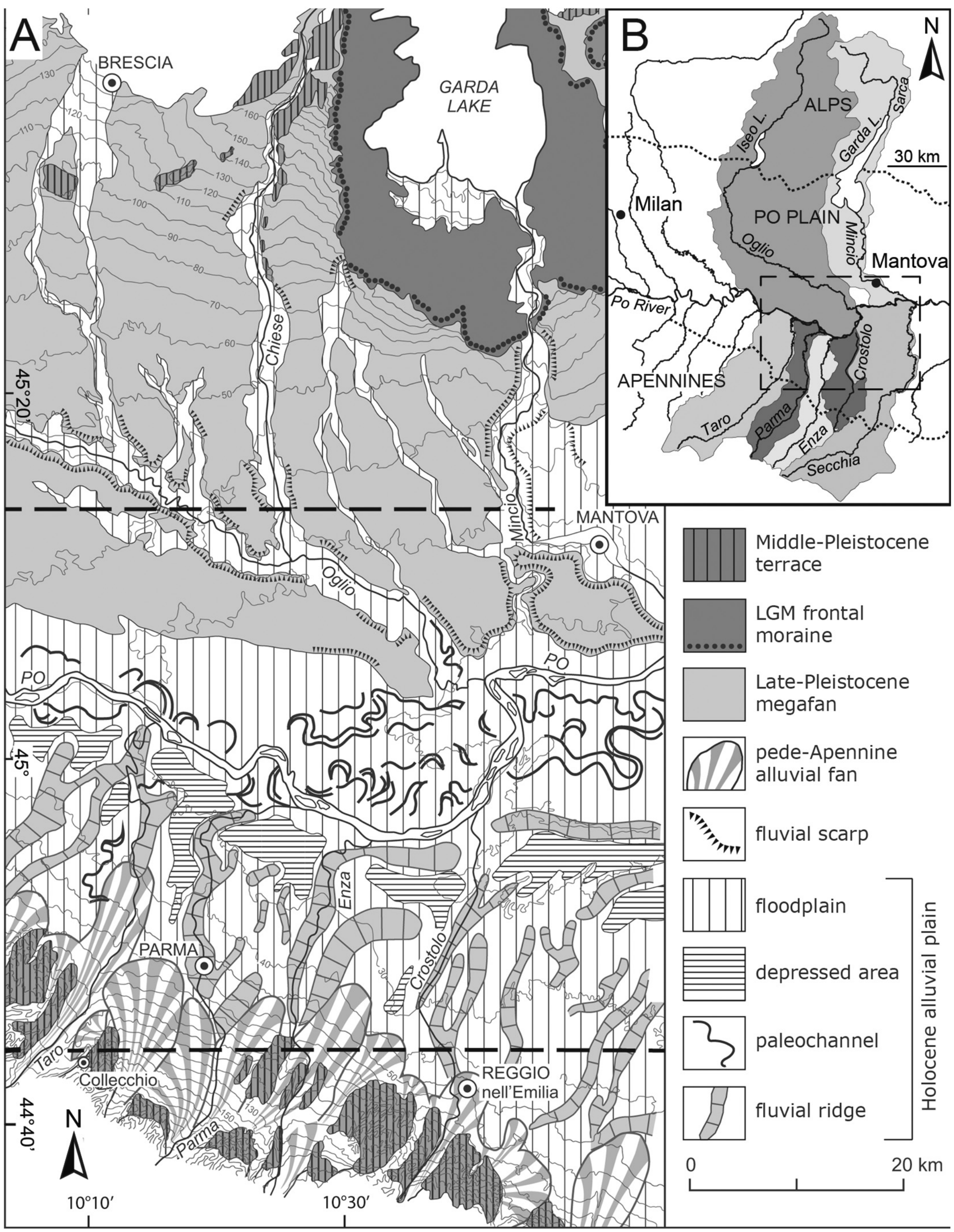

Fig. 2. (A) Geomorphological map (from Cremaschi and Nicosia, 2012), showing the main landforms of the central Po Plain and of the Alpine and Apennine piedmont regions. Dashed lines are the northern and southern boundaries of the study area. LGM: Last Glacial Maximum. (B) Drainage area of the main rivers dissecting the study area (dashed rectangle). Note the larger areal extent of the Alpine drainage areas (including the sector upstream of the perialpine lakes). Dotted line is the boundary between the alluvial plain and mountain areas.

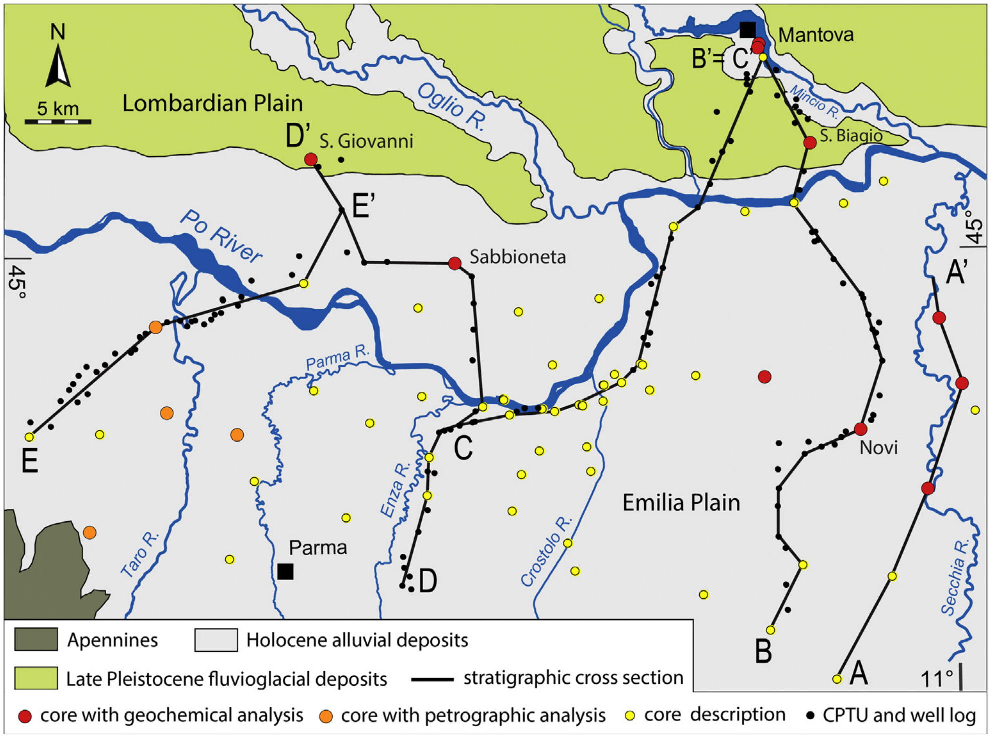

Fig. 3. Study area, with location of the stratigraphic data used in this work and of cross sections AA′ (Fig. 4), BB′ (Fig. 7), CC′ (Fig. 8), DD′ (Fig. 9), and EE′ (Fig. 10).

(Ravazzi et al., 2012a, 2014; Monegato et al., 2017). The Oglio and Mincio rivers flow along valleys incised into LGM fluvioglacial deposits and bounded by converging scarps (Fig. 2a) with maximum heights of 50 m that become progressively lower towards the Po (Fontana et al., 2014). A fluvial scarp parallel to the Po River locally separates the fluvioglacial Alpine units from Po fluvial deposits (Castiglioni, 2001; Cremaschi and Nicosia, 2012).

The southern region, locally named the *Emilia Plain*, is fed by Apenninic rivers with catchment areas <2300 km^2 and with a typical torrential regime. From west to east, the major rivers are the Taro, Parma, Enza, Crostolo and Secchia (Fig. 3). Gravelly alluvial fans crop out close to the Apennine margin, in the southwestern sector of the study area (Fig. 2a). Fine-grained alluvial plain sediments, with subordinate ribbon-shaped fluvial sands, are dominant instead downdip (Fig. 2a). Based on archaeological findings, the oldest deposits exposed in this portion of the study area are dated to the late Bronze Age (i.e., ~3000 cal ky BP; Cremaschi et al., 2006).

2.3. Subsurface stratigraphy of the Po Basin

The subsurface stratigraphy of the Po Plain has been investigated at the basin scale through interpretation of deep seismic profiles and well logs (Pieri and Groppi, 1981). According to these studies, the Po Basin fill consists of a shallowing-upward succession of deep marine to continental Pliocene-Quaternary sediments (Ricci Lucchi, 1986). The thickness of the sedimentary infill locally exceeds 8 km (Mariotti and Doglioni, 2000).

Continental deposits are mostly younger than 0.87 Ma (Muttoni et al., 2003), and their internal architecture reflects the Middle-Late Pleistocene alternation of glacial and interglacial periods (Amorosi et al., 2008). Due to high subsidence rates (~1 mm/yr in the last 125 ky, Antonioli et al., 2009), a ~100 m-thick dominantly aggradational sequence accumulated during each ~100 ky glacial/interglacial cycle. Each sequence is composed of laterally extensive, sheet-like fluvial channel bodies deposited during glacial periods, overlain by thick overbank facies, which accumulated mostly during the interglacials (Amorosi et al., 2008).

Recent studies from the southern Po Plain (Amorosi et al., 2016a, 2017a), between the Apennine chain and the Po River, have investigated in detail the Late Pleistocene to Holocene sequence (last ~100 ky). The Late Pleistocene succession is characterized by a systematic bipartite zonation into (i) a sand-dominated portion in the north, with vertically amalgamated channel belts related to the Po River, and (ii) a mud-prone portion in the south, fed by Apenninic rivers (Fig. 4). Sands are subordinate in the Apenninic domain and consist of isolated lenticular bodies, generally <4 m thick (Bruno et al., 2017a). Floodplain muds are marked at various levels by weakly developed paleosols (Inceptisols of Soil Survey Staff, 1999; see also Amorosi et al., 2015, 2017a), testifying to relatively short-lived (a few thousand years) phases of river entrenchment associated with a substantial drop of sea level (~30–50 m between 30 and 24 cal ky BP, Lambeck et al., 2002; Peltier and Fairbanks, 2006). The Holocene succession records a widespread development of poorly drained and swampy areas, likely reflecting the post-LGM sea-level rise (Campo et al., 2016). Most of these swamps were reclaimed in the last centuries.

3. Methods

An area of ~2200 km^2 was investigated through correlation of a large quantity of stratigraphic data, including 25 core logs, 40 piezocone tests (CPTUs) and 78 well logs. Core logs are from the stratigraphic database of the Emilia-Romagna Geological Survey, with the exception of cores MN1 and FOR6, which are reported in Amorosi et al. (2008) and Ravazzi et al. (2013), respectively. Piezocone tests and water-well logs are from the stratigraphic databases of Lombardia and Emilia-Romagna geological surveys. All data were plotted on four stratigraphic cross sections (locations on Fig. 3) to a depth of about 80 m.

Five cores (S. Biagio, Novi, Mantova, Sabbioneta and S. Giovanni), recovered between May 2013 and March 2016, were used as reference points for facies characterization. The S. Biagio core is part of an extensive drilling project supported by ExxonMobil Upstream Research Company. The Novi and Mantova cores were acquired by Regione Emilia-Romagna and Provincia di Mantova, respectively. The Sabbioneta and S. Giovanni cores were drilled by Regione Lombardia and Centro Nazionale

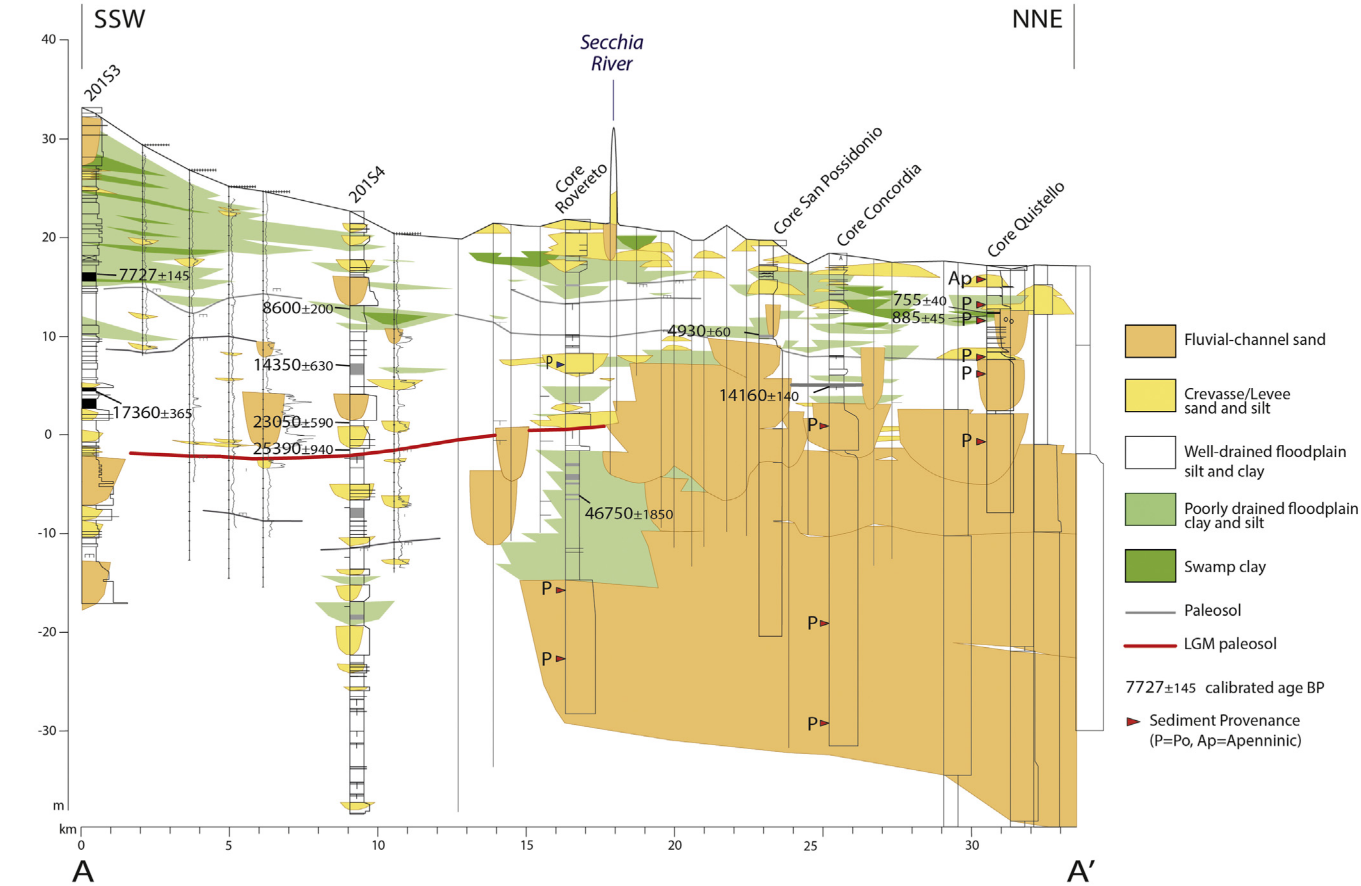

Fig. 4. Stratigraphic cross-section (AA′) depicting the late Quaternary stratigraphy of the southern Po Plain. Location in Fig. 3. Modified after Amorosi et al. (2016a).

Ricerche-Istituto per la Dinamica dei Processi Ambientali (CNR-IDPA) in the framework of the EU project "GeoMol" (Alpine Space Program).

The interpretation of CPTU tests was based on Amorosi and Marchi (1999) and Amorosi et al. (2017a). Two CPTUs performed adjacent to the Sabbioneta and S. Giovanni cores were used for facies calibration. Simple lithologic descriptions of water-well cuttings (e.g., sand vs. clay) were used to constrain the geometries of fluvial-channel sediment bodies following calibration with nearby core descriptions.

Cores were sampled for geochemical and ^{14}C analyses. Thirty-two sediment samples were analyzed by X-Ray Fluorescence (XRF) Spectrometry at Bologna University laboratories in order to define sediment provenance. Major element concentrations were calculated using the method of Franzini et al. (1975), while the coefficients of Franzini et al. (1972), Leoni and Saitta (1976) and Leoni et al. (1986) were used for trace elements. Additional geochemical and petrographic data on sediment provenance are from Amorosi et al. (2016a) - see Fig. 3) and the Geological Map of Italy (scale 1:50,000; Sheet 181).

Eight samples of peat and wood were collected for radiocarbon analysis. Samples were collected from the central part of the core to avoid drilling fluid contamination, and dried in a 40 °C oven. Acid-alkali-acid pretreatment was carried out before AMS counting at Queens University Laboratory (Belfast, Northern Ireland) and at Kigam Laboratory (Korea Institute of Geoscience and Mineral Resources, Daejeon, Republic of Korea). ^{14}C ages were calibrated using OxCal 4.2 (Bronk Ramsey and Lee, 2013) with the IntCal 13 curve (Reimer et al., 2013). The chronological framework was also based on additional 20 radiocarbon dates from previously published papers (Amorosi et al., 2008; Ravazzi et al., 2013; Campo et al., 2016) and from the Geological Map of Italy (sheets 181, 182 and 201, see Table 1).

4. Core analysis

4.1. Sedimentology

Detailed core analysis enabled the identification of five facies associations based on lithology, grain size trends, color, consistency, and accessory material (wood, vegetal remains, carbonate concretions, macrofossils).

4.1.1. Fluvial-channel facies association (FC)

4.1.1.1. Description. This facies association is composed of coarse to fine gray sand, with an erosive base (Fig. 5) and internal fining-upward (FU) trend. The transition to the overlying muds is gradational and marked by cm-thick clayey layers. Small pebbles (maximum diameter = 2 cm) were seldom recorded at the base. Macrofossils are absent, and wood fragments and vegetal remains are rare. Individual sand bodies are 4 to 13 m thick. Amalgamated sand bodies may locally exceed 30 m in thickness. Tip resistance values (q_c) from CPTU tests are typically >3 MPa and show a decreasing upward trends. Pore pressure values (u) are negative.

4.1.1.2. Interpretation. Based on lithology, grain size trends, types of stratigraphic contacts, thickness, and accessory material, we interpret this facies association as fluvial-channel deposits. Decreasing-upward q_c values reflect fining-upward grain size trends, whereas negative u values indicate that pore pressure is dissipated rapidly due to high permeability. The upward transition to thick mud deposits suggests channel abandonment with the re-establishment of floodplain environments.

Table 1
List of radiocarbon dates. GMI: Geological Map of Italy.

Core	Sample depth (m)	Sample elevation (m asl)	Dated material	^{14}C age (y BP)	Calibrated 2σ range (y BP)	Calibrated mean ± σ (y BP)	Laboratory	Source	Fig.
Mantova	8.9	11	Peat	530 ± 20	555–515	545 ± 25	Kigam (Korea)	This work	7
FOR 6	2.7	11	Wood	3025 ± 35	3350–3140	3230 ± 60	Uppsala (Sweden)	Ravazzi et al., 2013	6
182 S15	10.3	11.2	Organic clay	4930 ± 80	5896–5485	5680 ± 95	Enea (Italy)	Pavesi, 2009	7
182 S2	12.3	18.7	Wood	5030 ± 40	5896–5661	5780 ± 120	Enea (Italy)	GMI	8
182 BVM4	10.2	18.2	Wood	7400 ± 100	8388–8018	8200 ± 180	Enea (Italy)	GMI	8
165SO P503	20.2	−0.2	Organic clay	8240 ± 50	9402–9032	9210 ± 90	Enea (Italy)	Campo et al., 2016	6
182 S14	9	13.1	Organic clay	8420 ± 150	9732–9012	9395 ± 180	Enea (Italy)	Pavesi, 2009	7
181 S2	8.3	51.2	Organic clay	11,360 ± 300	13,840–12,690	13,240 ± 300	Enea (Italy)	GMI	9
182 S15	19.5	3	Wood	15,450 ± 130	18,967–18,429	18,715 ± 130	Enea (Italy)	Pavesi, 2009	7
182 S14	19.8	1.2	Wood	16,250 ± 230	20,169–19,020	19,620 ± 290	Enea (Italy)	Pavesi, 2009	7
182 S14	22.8	−0.7	Wood	17,550 ± 280	21,496–20,511	21,230 ± 370	Enea (Italy)	Pavesi, 2009	7
182 S14	23	−0.9	Organic clay	22,100 ± 330	27,168–25,806	26,400 ± 360	Enea (Italy)	Pavesi, 2009	7
201 S10	24.5	8	Organic clay	22,670 ± 280	27,510–26,310	26,900 ± 600	Beta Analytic (USA)	GMI	6
181 S2	24.8	34.7	Organic clay	22,600 ± 900	28,800–25,200	26,940 ± 890	Enea (Italy)	GMI	9
S. Biagio	10.5	7.9	Wood	23,080 ± 140	27,640–27,120	27,390 ± 130	Kigam (Korea)	This work	6
S. Giovanni	4.4	22.2	Wood	23,300 ± 190	27,820–27,240	27,530 ± 140	Belfast (N·Ireland)	This work	8
S. Giovanni	8.1	18.5	Peat	25,560 ± 250	30,470–29,060	29,750 ± 360	Belfast (N·Ireland)	This work	8
182 S15	34.7	−12.2	Wood	27,300 ± 600	32,961–30,371	31,380 ± 640	Enea (Italy)	Pavesi, 2009	7
182 S2	32.7	−1.7	Organic clay	28,600 ± 200	33,315–31,860	32,600 ± 700	Enea (Italy)	GMI	8
Novi	26.6	3.8	Wood	32,900 ± 330	38,160–36,220	37,100 ± 520	Kigam (Korea)	This work	6
Mantova	16.2	3.8	Peat	37,000 ± 240	42,000–41,150	41,580 ± 210	Kigam (Korea)	This work	7
MN1	18.8	−2.5	Organic clay	38,600 ± 1050	44,750–41,270	42,900 ± 900	Enea (Italy)	Amorosi et al., 2008	6–7
182 S9	29.8	−6.8	Organic clay	39,100 ± 1150	45,340–41,560	43,500 ± 1900	Enea (Italy)	GMI	8
182 S14	32.9	−10.8	Peat	39,900 ± 650	44,803–42,640	43,630 ± 560	Enea (Italy)	Pavesi, 2009	7
Sabbioneta	19.4	1	Wood	40,375 ± 1490	47,650–42,030	44,500 ± 1430	Belfast (N·Ireland)	This work	8
182 S10	30.5	−8.9	Organic clay	47,900 ± 550	49,087–46,866	48,000 ± 1000	Enea (Italy)	GMI	7
MN1	27.7	−6.4	Organic clay	>45,000	no calib		Enea (Italy)	Amorosi et al., 2008	6–7
182 S15	45	−22.5	Organic clay	>45,000	no calib		Enea (Italy)	Pavesi, 2009	7
S. Giovanni	23.1	3.4	Organic clay	>49,280	no calib		Belfast (N·Ireland)	This work	8

4.1.2. Crevasse and levee facies association (CL)

4.1.2.1. Description. This facies association consists of ≤2 m-thick fine to silty sand bodies, with either a sharp or a gradational base. Sand bodies with sharp bases generally have internal FU trends and gradational tops. Sand bodies with gradational bases show internal coarsening upward (CU) trends and sharp contacts with the overlying muds. Sand-silt alternations on a cm-thick scale are also common. The color is gray or brown, with occasional mottles due to Fe oxides. Macrofossils are absent, whereas wood fragments and vegetal remains were seldom encountered. In CPTUs, q_c ranges between 3 and 20 MPa, whereas u values fluctuate between <0 and > u_0 (static equilibrium pore pressure).

4.1.2.2. Interpretation. The thin sand-clay alternations reflect a flood pulse energy regime. The absence of macrofossils and the presence of rare floated woods and plant remains link this energy regime to fluvial activity. Multiple overflow events led to the formation of up to 2 m-thick sediment bodies (i.e., channel levees). We interpret coarsening-upward sands with gradual bases and sharply defined tops to reflect the progressive crevassing of channel levees and the consequent spread of progressively coarser material in wide splays. We interpret fining-upward sands with sharp bases and gradual tops as the result of conveyed bedload transport and deposition in ephemeral channels after complete crevassing.

4.1.3. Well-drained floodplain facies association (F)

4.1.3.1. Description. This facies association is composed of massive, variably-colored clayey silt and silty clay, with subordinate sandy silt. Reddish mottles due to Fe oxides and carbonate concretions occur in discrete horizons. Calcic horizons are hardened and frequently overlain by decimeter-thick, carbonate-free strata, enriched in dark, decomposed organic material. Fossils, wood fragments and vegetal remains were not encountered. In situ pocket penetration (PP) tests yielded values >2 kg/cm^2. In CPTUs, q_c ranges between 1 and 3 MPa, and f_s (lateral friction) between 50 and 150 kPa. Pore pressure is $>> u_0$.

4.1.3.2. Interpretation. We interpret fossil free muds as having been deposited at distal locations from an active channel during major flood events (floodplain). Changes in color and carbonate content along the vertical profile reflect pedogenic processes. Dark, organic-matter-rich, carbonate-free horizons with associated, underlying calcic horizons have been interpreted as A and Bk horizons, respectively, of weakly developed paleosols (Inceptisols of Soil Survey Staff, 1999, 2014). These soils formed in response to periods of subaerial exposure on the order of a few thousand years (see Amorosi et al., 2014a). Oxidation, carbonate leaching from the topsoil, and accumulation in the calcic horizon require the presence of a vadose zone, and thus, a low water table (i.e., well-drained conditions). Subaerial exposure and accumulation of secondary calcite in the Bk horizons resulted in high soil consistency as highlighted by pocket penetration and CPTU test values. High u values reflect a low permeability, typical of fine-grained materials.

4.1.4. Poorly-drained floodplain facies association (PdF)

4.1.4.1. Description. This facies association has been encountered only in core Novi, where it consists of a 30 cm-thick succession of soft, gray silty clays with sparse vegetal remains and no traces of oxidation. Carbonate concretions and fossils are absent. In situ pocket penetration tests yielded values in the range of 1–2 kg/cm^2. This facies association is poorly represented in the analyzed cores. On the contrary, many core descriptions from the stratigraphic database (see Section 3) report depositional facies with similar characteristics. For diagnostic CPTU features of this facies association, the reader is referred to Amorosi et al. (2017a) and Bruno et al. (2017a), where this facies association is characterized by tip resistance values of 0.8–1.2 MPa and pore pressure $>> u_0$.

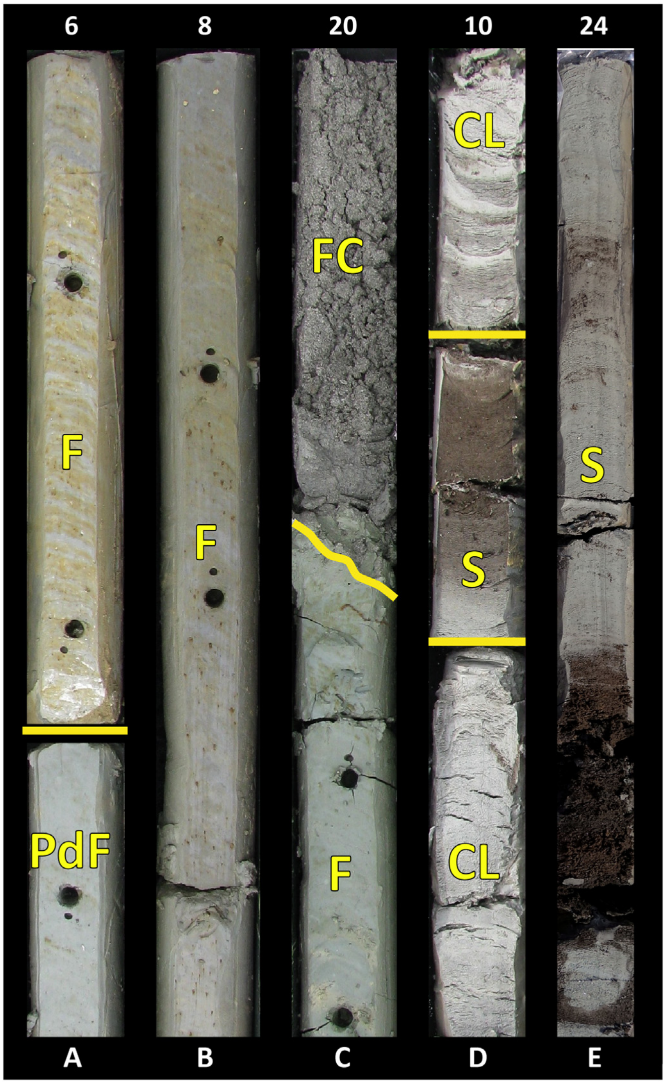

Fig. 5. Representative core photographs of the facies associations identified in the studied cores. Legend: FC: fluvial channel; F: floodplain; PdF: poorly drained floodplain; S: swamp; CL: crevasse and levee. Core segments are 80 cm long. Core depth (m) is indicated at the top of each core segment. A, B and C are from core 'Novi'. D is from core 'S. Biagio' and E is from core 'S. Giovanni'.

4.1.4.2. Interpretation. Because of the dominance of fine-grained material, we interpret this facies association as having been deposited in a floodplain. The poor consistency (highlighted by low PP and q_c values) and the absence of traces of oxidation and carbonate concretions suggest the persistence of poorly drained conditions after deposition (or rapid burial), preventing the onset of soil forming processes.

4.1.5. Swamp facies association (S)

4.1.5.1. Description. This facies association is composed of very soft gray clay with subordinate silt and silty clay. Undecomposed vegetal remains and wood fragments are abundant. Peat layers up to 20 cm thick occur at various levels. Freshwater fossils (e.g., *Pisidium*) are locally encountered. Neither traces of oxidation nor carbonate concretions were observed. Maximum thickness is 2 m. Pocket penetration values are <1 kg/cm^2. Tip-resistance values are <0.8 MPa and $u \gg u_0$.

4.1.5.2. Interpretation. The dominance of fine-grained material suggests that this facies association was deposited in a low-energy environment away from an active channel. The absence of oxidation and carbonate concretions indicates reducing conditions, likely reflecting the presence of stagnant waters (swamp). This interpretation is supported by low PP and q_c values and by the abundance of freshwater fossils, peat and undecomposed organic material.

4.2. Geochemical signature of Po versus alpine rivers

A large body of research (Amorosi and Sammartino, 2017, and references therein) has shown that ultramafic (ophiolite) complexes that crop out in the western Alps and at the north-western tip of the northern Apennines may deliver large volumes of Cr-rich and Ni-rich detritus to the alluvial and coastal portions of the Po River system. In Po Plain deposits, lithofacies assemblages generated from ophiolite-rich sources of the western Po River catchment invariably exhibit higher Cr and Ni values than sediment delivered from southern (Apenninic) or northern Alpine river catchments that contain unimportant ultramafic detritus. Consequently, these metals can be used as geochemical tracers of Po River provenance across downdip segments of the Po Plain.

The element ratio Cr/Al_2O_3 tested successfully in Po Plain sediments for the discrimination of mafic/ultramafic versus non-mafic/ultramafic source rock composition (Amorosi et al., 2002; Dinelli et al., 2007; Amorosi, 2012; Di Giuseppe et al., 2016). The use of Al_2O_3 as a grain size proxy allows us to compensate for mineralogical and granular variability of Cr concentrations (Liaghati et al., 2003).

To identify Alpine versus Po River sediment sources, 32 core samples were selected for whole-rock geochemistry. We collected two samples from Core Novi, 13 from Core San Biagio, 6 from Core Mantova, 6 from Core Sabbioneta and 5 from Core San Giovanni (Fig. 6). Sediment composition of cored material was matched against (i) core samples of known (Po River) sediment provenance from an adjacent area (Fig. 4, Amorosi et al., 2017a) and (ii) sediment samples from the modern Po, Oglio, Mincio and Adige rivers (data from Amorosi and Sammartino, 2017).

The overlapping trend in composition between sediment samples from the study cores and modern river sediments allows us to differentiate sediment delivered to the study area from Alpine sources (cores from S. Biagio, Mantova and S. Giovanni) from material supplied by the Po River (core from Novi). Northern Alpine sources (Oglio and Mincio rivers) appear to be the most likely sediment contributors to the study area. In core Sabbioneta, the analysis of selected trace metals and major elements reveals a prominent shift in sediment composition across an amalgamation surface around 14 m deep that separates two fluvial-channel sand bodies with distinct sediment provenance (Fig. 5). Below this surface, Cr/Al_2O_3 values plot close to the field of modern Alpine rivers (Fig. 5). Higher up in the stratigraphic column, core samples typically exhibit high Cr/Al_2O_3 values, which reflect affinity to the composition of modern Po River sediment. The widespread distribution of individual plots in the binary diagram reflects changes in grain size (Amorosi et al., 2014b). With an increasing clay proportion, samples from a given provenance domain exhibit increasingly higher Cr and Cr/Al_2O_3 values.

5. Late Pleistocene and Holocene stratigraphy of the central Po Plain

The depositional architecture of the central Po Plain was reconstructed through stratigraphic correlation along four stratigraphic panels (Figs. 6–9; location in Fig. 3). Stratigraphic data ($n = 50$) were plotted on the 53 km-long cross section BB′ (Fig. 6) that extends from the Apenninic margin to the town of Mantova, 12 km north of the Po River (Fig. 3). South of core Novi, a thick package of pedogenized muds represents the dominant lithologic feature (Fig. 7). Fluvial sand bodies are strongly lenticular and <10 m thick. A weakly developed paleosol, dated to ~27 ky BP (see core 201 S10, Fig. 7 and Table 1) is the most prominent stratigraphic marker across this sector. Poorly drained floodplain deposits are increasingly abundant up-section.

A 20 km-wide and 20-m thick, multistory fluvial-channel sand body, with its top about 13 m deep, is widely developed between core Novi and the Po River (Fig. 7). Sand bodies of comparable size and lithologic characteristics are also observed in cross sections CC′, DD′ and EE′

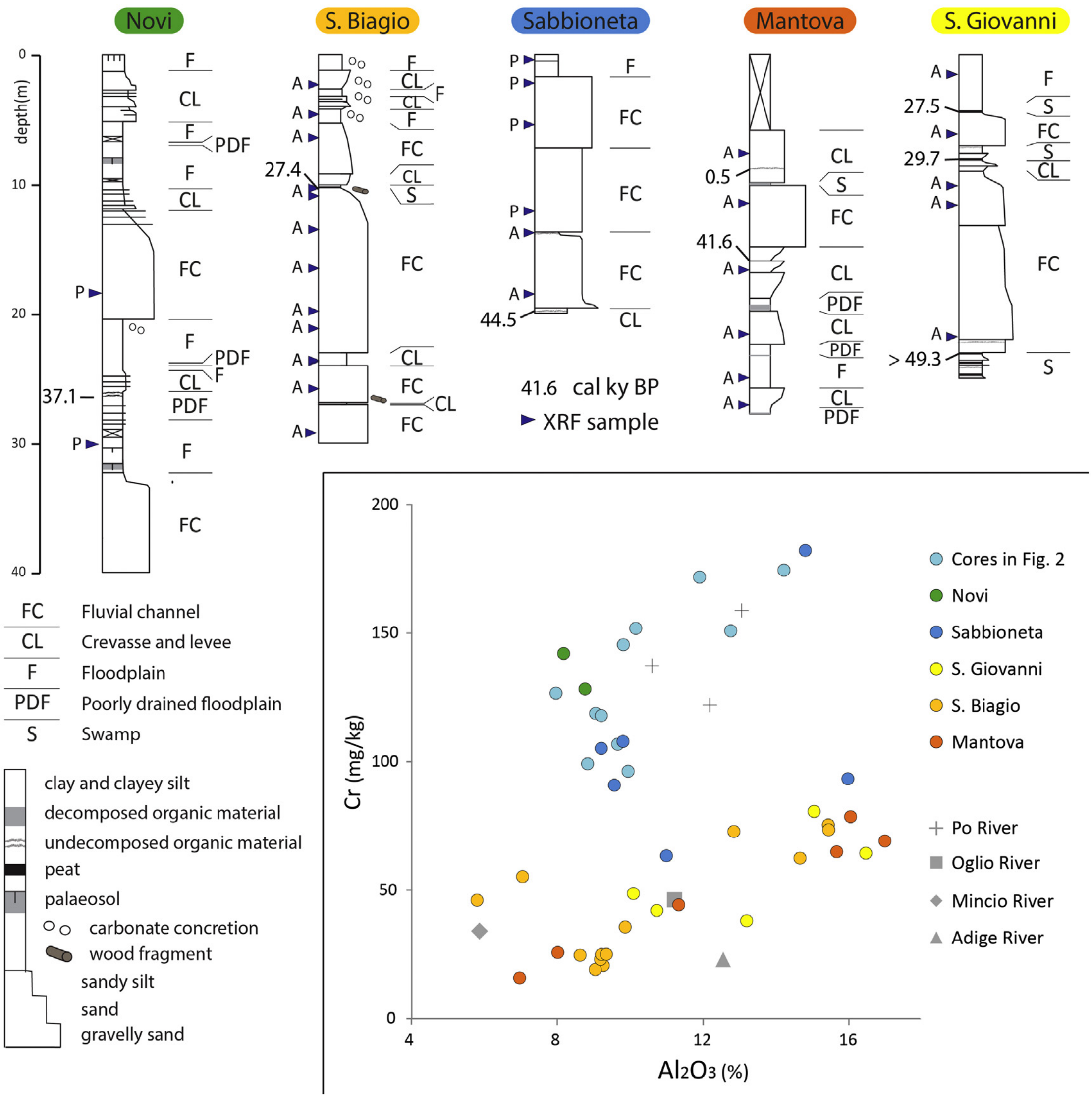

Fig. 6. Stratigraphic log of analyzed cores and scatterplots of Al_2O_3 versus Cr from 43 core samples (in color), showing natural metal concentrations as a function of sediment provenance and grain size. Average compositions of modern river sediments are shown in gray.

(Figs. 8, 9, and 10). Based on radiocarbon dates from cores 165SO P503 (Fig. 7), 182 S14 and 182 S15 (Fig. 8), these sands were assigned to the Late Pleistocene between about 40 and 10 ky BP (Table 1). The boundary between Late Pleistocene and Holocene fluvial-channel deposits is difficult to identify in cross sections DD′ (Fig. 9) and EE′ (Fig. 10) due to the lack of chronologic data. Based on high Cr and Ni contents from core Novi (Fig. 5) and on the feldspatolithoquartzose metamorphiclastic sand composition from core 181 S10 (Fig. 9), these sands are interpreted to represent a fluvial channel-belt ascribed to a paleo-Po River (Garzanti et al., 2011) flowing with a W-E orientation.

In the Lombardian Plain, north of Po River, the Holocene succession is restricted to small areas close to the Mincio River (cores FOR 6 and Mantova in Figs. 7 and 8, respectively). In this part of the Po Plain, LGM deposits may be shallowly buried and even outcropping (i.e., core S. Giovanni in Fig. 9). Consistent with its geographic position, fluvial-channel sand in this area closely reflects a northern Alpine provenance (see geochemical data from cores S. Biagio, Mantova and S. Giovanni, in Figs. 7, 8 and 9, respectively). The boundary between sands of Alpine versus Po River composition has been observed about 14 m deep in core Sabbioneta (Figs. 6 and 9) where sediment sourced from the northern Alps is sharply overlain by Po River sands. In other areas, the boundary between Alpine and Po sands (dashed line in Figs. 7–10) was traced tentatively because of the lack of compositional data. It is noteworthy that in many parts of the plain the Po River sands are laterally juxtaposed to older Alpine deposits. In cross section BB′ (Fig. 7), for example, a peat layer dated to 9.2 cal ky BP in core 165SO P503 lies at an elevation ~8 m lower than a significantly older peat layer dated to ~27 cal ky BP (core S. Biagio), only 4 km to the north.

6. Discussion

6.1. Aggradation and incision in the central Po Plain during the last 30 ky

Alternating phases of aggradation and incision in the Po Plain, related to climatic or eustatic variations, have been reported by several recent papers (Ravazzi et al., 2012b; Fontana et al., 2014; Amorosi et al., 2017a, 2017b; Bruno et al., 2017a). However, based on these studies, aggradation and incision did not occur synchronously across the Po Plain. A contrasting sedimentary response is recorded between the southern Alpine river systems and the Po-Apenninic region. In the southern Po Plain, a phase of incision led to the development of an Inceptisol between 30 and 24 cal ky BP (Amorosi et al., 2017a). At the same time, aggradation (~1.4 mm/yr, Fontana et al., 2014) took place in the main Alpine depositional systems where sedimentation ceased around 18–17 cal ky BP

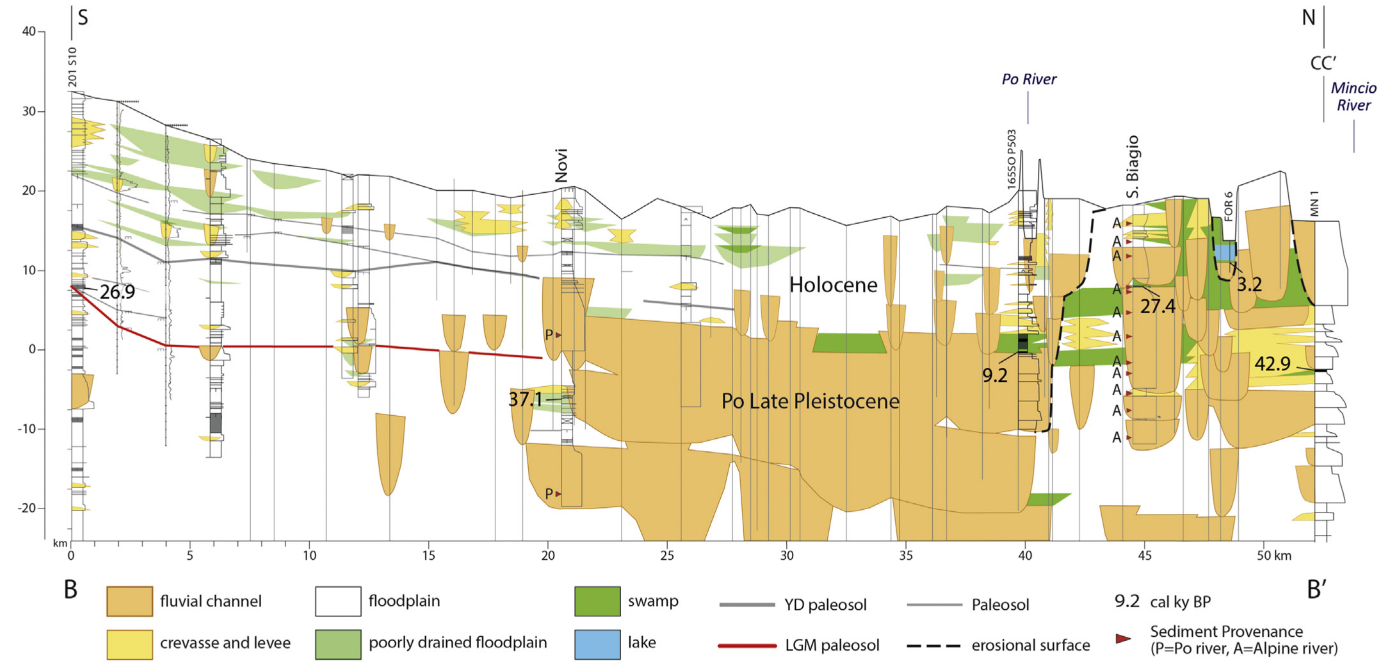

Fig. 7. Stratigraphic panel (BB′) depicting late Quaternary stratigraphy in the central Po Plain.
See Fig. 3 for location and Table 1 for details on radiocarbon dates.

(Fontana et al., 2008, 2014; Carton et al., 2009), and fluvial valleys were incised into LGM deposits. Low aggradation rates (<1 mm/yr) were recorded in the southern Po Plain between about 24 and 12.5 cal ky BP (Bruno et al., 2017b); renewed incision led to the development of another paleosol between 12.5 and 11.5 cal ky BP (YD paleosol of Amorosi et al., 2016b, 2017a). The onset of the Holocene records a period of widespread aggradation in the Po Plain (Bruno et al., 2017b).

Stratigraphic relationships at a regional scale between Apenninic, Po and Alpine deposits reconstructed through detailed correlations across four cross sections confirm the decoupled sedimentary response of Po and southern Alpine fluvial systems.

Fluvial stratigraphic architecture in the central Po Plain is characterized by a tripartite subdivision (Fig. 7) into (i) a mud-dominated sector in the south, (ii) a central sector with thick sand bodies at depths > 13 m, and (iii) a sand-dominated sector in the north. Based on hundreds of near-surface samples from the southern Po Plain (Amorosi et al., 2014b), we infer that the southern sector (close to the Apenninic chain) was fed by the Apenninic fluvial system. In this area, exposed sediments

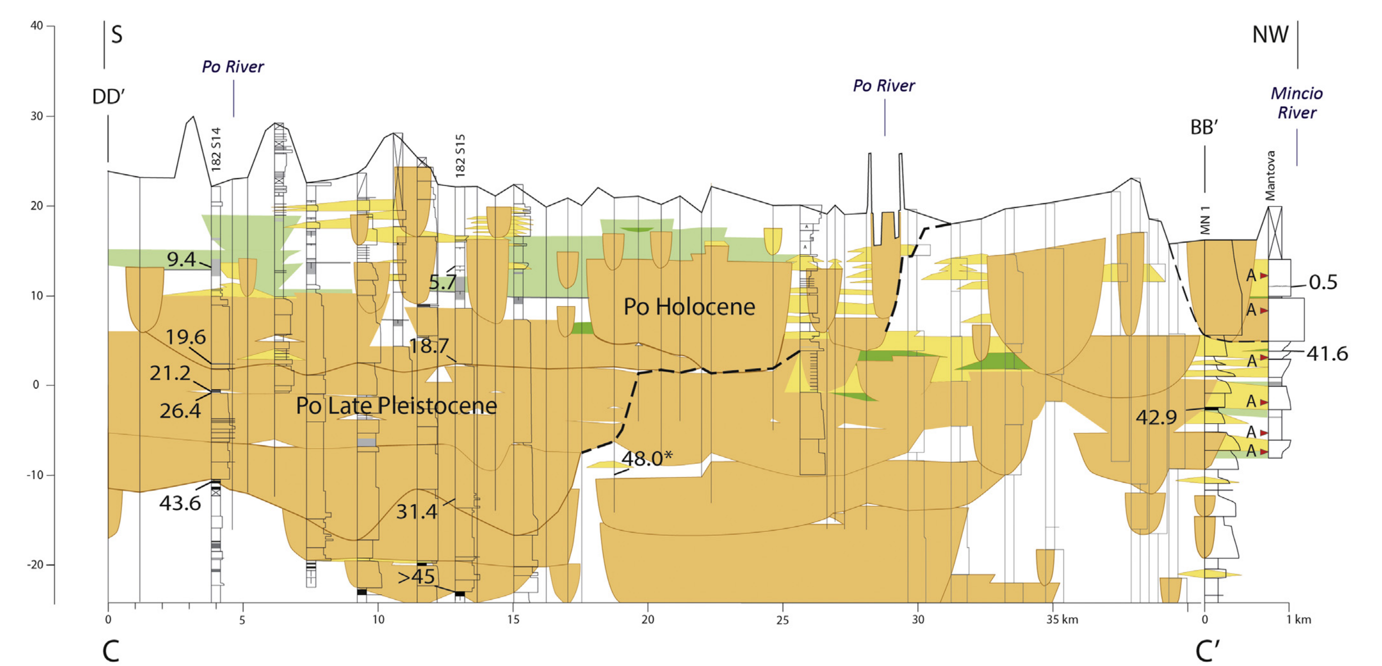

Fig. 8. Stratigraphic panel (CC′) depicting late Quaternary stratigraphy in the central Po Plain.
See Fig. 3 for location, Fig. 7 for legend and Table 1 for details on radiocarbon dates. Dates with asterisks are projected from nearby cores.

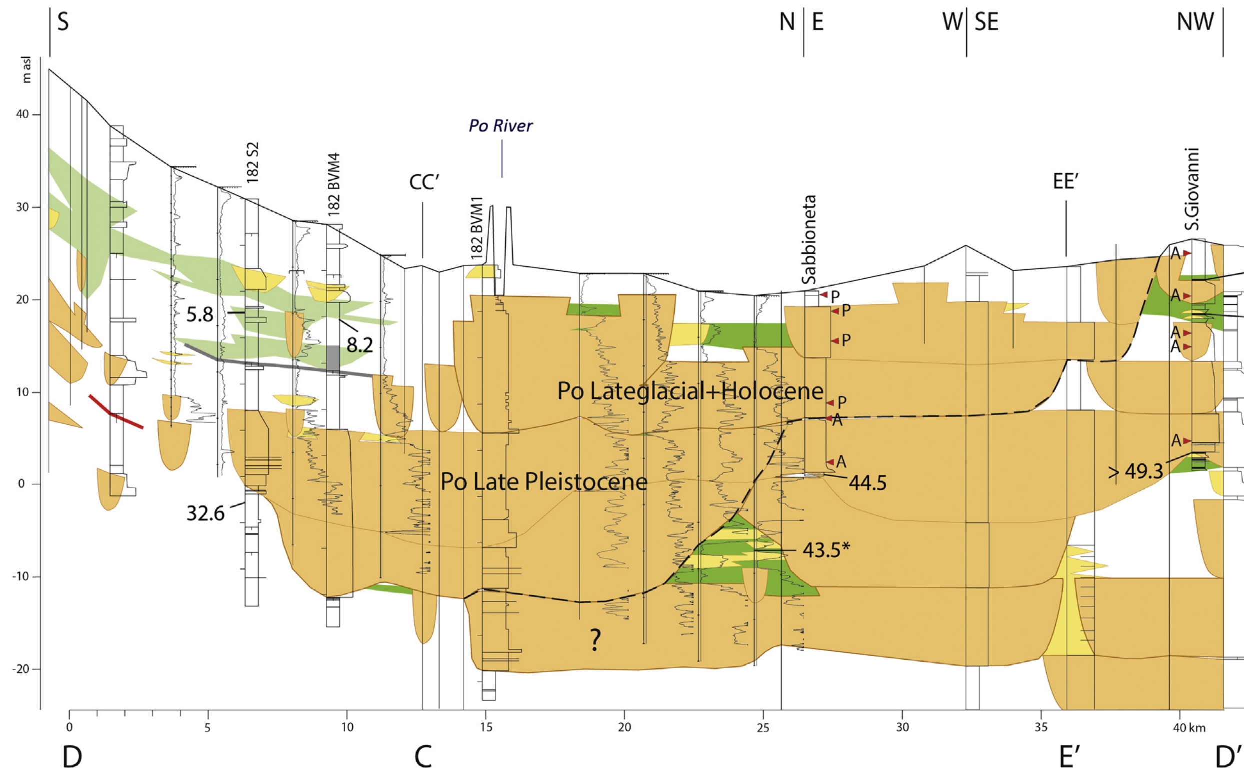

Fig. 9. Stratigraphic panel (DD′) depicting late Quaternary stratigraphy in the central Po Plain. See Fig. 3 for location, Fig. 7 for legend and Table 1 for details on radiocarbon dates. Dates with asterisks are projected from nearby cores.

are predominantly fine-grained (Fig. 2a), whereas fluvial sands are constrained in a network of isolated ribbons (Castiglioni, 1997). A thick succession of pedogenized muds with similar characteristics has been identified about 50 km east of the study area, and attributed to the Apenninic fluvial system based on compositional data (Bruno et al., 2017a). The abundance of mud in the southern Po Plain likely reflects the abundance of clays in the Apenninic catchments and their relatively small drainage area (typically <2300 km^2, Fig. 2b). The weakly developed paleosol dated to 27 cal ky BP in cores 201 S10 and 181 S2 (red line in Figs. 6 and 9) is apparently correlative with the Inceptisol recently identified across a wide portion of the eastern Po Plain (LGM paleosol of Amorosi et al., 2017a; Morelli et al., 2017). We interpret this paleosol, traceable northwards into coeval Po channel sands (see radiocarbon dates in Fig. 8), to represent a relatively short phase of channel incision that occurred at the onset of the LGM (MIS 3-2 transition). Another buried paleosol, mapped in the eastern Po Plain (YD paleosol, after Amorosi et al., 2017a; Morelli et al., 2017), testifies to a more recent phase of incision that occurred at the onset of the Younger Dryas cooling event. We did not observe the YD paleosol in the analyzed cores, but diagnostic geotechnical features from CPTU tests suggest this pedogenized horizon was likely present across the study area (Figs. 7, 9, and 10).

The Late Pleistocene Po fluvial-channel sand body exhibits a sharp boundary to the south with floodplain muds of Apenninic provenance (Figs. 7, 9, and 10). In contrast, no changes in lithology are associated in the north with the boundary between Po and northern Alpine deposits. We tentatively traced this boundary in the subsurface, within seemingly homogeneous sandy deposits, with the aid of compositional and radiocarbon data (see dashed line in Figs. 7–10). The offset between Po and Alpine LGM deposits (Fig. 7) cannot be related to recent tectonic movements, as the most external structures of the Alpine chain are located ~20 km north of the study area (Fig. 1). We infer, instead, that it resulted from erosion due to Po River activity. This hypothesis is substantiated by the well-defined fluvial scarp morphology that separates in outcrop Po River deposits from units of Alpine composition a few kilometers west of the study area (Castiglioni, 2001). Therefore, the geometry of the boundary between Po and northern Alpine sediments is the result of the complex series of depositional and erosional events that occurred in the last 30 ky BP.

At the onset of the LGM (Fig. 11a), the central Po Plain was affected by fluvial incision/lateral migration in the Po River area and by aggradation/progradation of the coeval Alpine fluvial systems. The phase of Po River incision may have lasted for a relatively short time interval compared to the subsequent period of lateral migration and valley filling. Indeed, radiocarbon dates from cores 182S14 and 182S15 (Fig. 8) suggest that valley filling was protracted for a large part of the LGM. After the LGM, widespread aggradation ceased in the Alpine river system and sedimentation was confined within narrow valleys (Fig. 11b). Chronological data do not allow precise dating of river entrenchment. We infer that entrenchment was almost simultaneous with glacier collapses around 18–17 cal ky BP (Ravazzi et al., 2012a, 2014), as postulated for the Venetian megafans (Monegato et al., 2007; Fontana et al., 2008). The last 18 cal ky BP also record an overall aggradation and northward migration of the Po River (Fig. 11b–c), with consequent erosion of the distal portion of the Alpine megafans (see erosional surface in Figs. 7–10). The northward migration of the Po River is attested to by the upsection transition from Alpine to Po sediments in core Sabbioneta (Fig. 9). Unfortunately, the lack of dateable material prevents the precise dating of this northward shift of the Po River.

6.2. Controlling factors

This study has shown that distinct sectors of the Po Basin responded to combined climatic and eustatic forcing at different times and in different ways. Sea-level fall is traditionally called into question to account for fluvial incision (Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1990; Zaitlin et al., 1994). However, recent works have demonstrated a more complex response of fluvial systems to sea-level oscillations (Törnqvist et al., 2000, 2003; Hori et al., 2002;

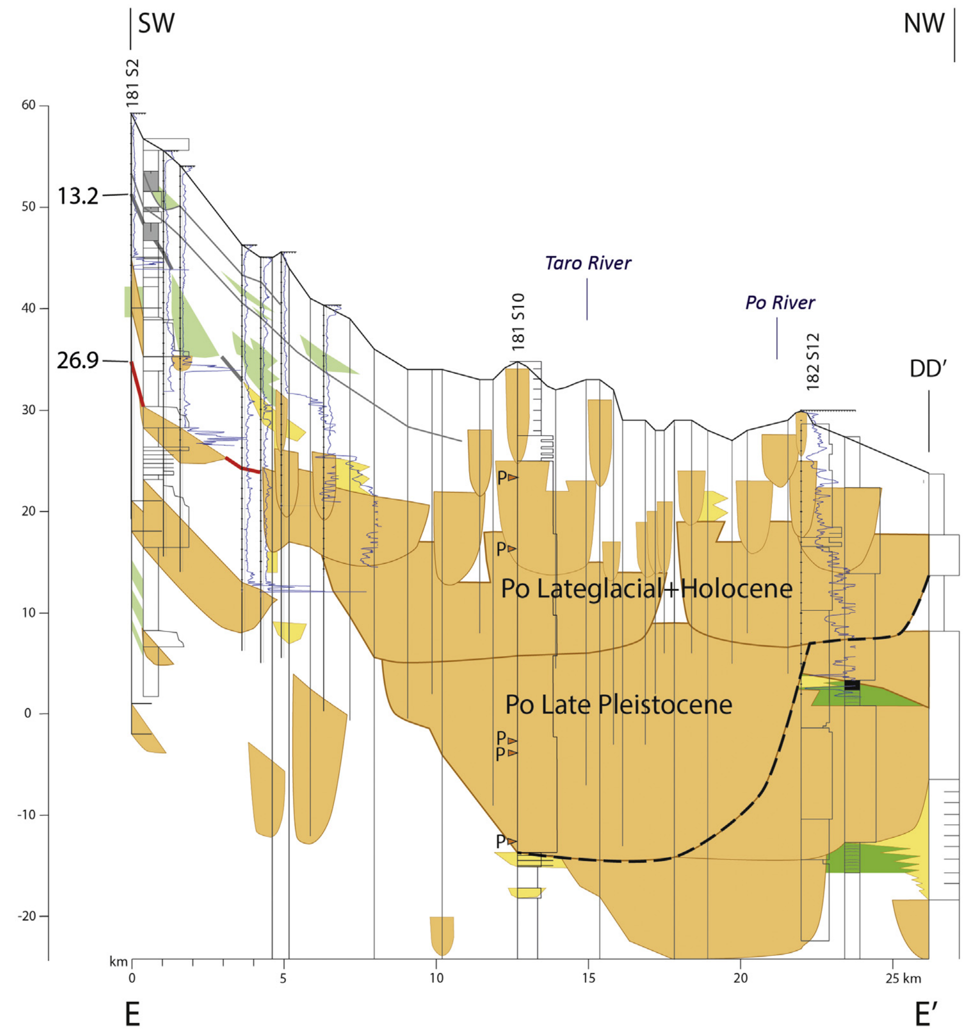

Fig. 10. Stratigraphic panel (EE′) depicting late Quaternary stratigraphy in the central Po Plain.
See Fig. 3 for location, Fig. 7 for legend and Table 1 for details on radiocarbon dates. Petrographic data in core 181 S10 are from Sheet 181 of the Geological Map of Italy at a scale of 1:50,000.

Wallinga et al., 2004; Shen et al., 2012). During the Late Pleistocene, the Po River did not excavate a deep, permanent valley in response to sea-level fall, as the effect of base-level drop was partly compensated by high subsidence rates (~1 mm/yr) and partly accommodated by channel pattern changes across the gently dipping Adriatic shelf (Amorosi et al., 2017a). A shallow, ephemeral valley formed at the onset of the LGM (Amorosi et al., 2017a) when the rate of sea-level fall exceeded subsidence rates.

As the trunk river represents the local base level for transverse river systems, incision by tributaries is expected in response to incision by the trunk river (Faulkner et al., 2016). Nevertheless, Alpine rivers aggraded onto the former alluvial plain between 30 and 24 cal ky BP (Fontana et al., 2014). Several studies have documented that base-level fall may locally induce aggradation when the river gradient is greater than the gradient of the exposed shelf (Miall, 1989; Schumm, 1993; Leckie, 1994; Browne and Naish, 2003; Fontana et al., 2008; Petter and Muto, 2008; Blum et al., 2013). A similar configuration characterizes the Lombardian Plain where the gradient of the Alpine tributaries is greater than the gradient of the Po Plain (Fontana et al., 2014), which is the landward extension of the Adriatic shelf. A schematic transversal section of the Po valley at the onset of LGM (~30–27 cal ky BP) is outlined in Fig. 11a. The dashed lines represent hypothetical longitudinal profiles of both Apenninic and Alpine tributaries. Local base-level fall in response to Po River incision induced incision only in the distal reaches of the Apenninic and Alpine tributaries, whereas aggradation is recorded at the basin margin (Fig. 11a).

Sediment accumulation in large outwash fans during glacial periods has been documented in many other studied sites (Ritter et al., 1995; Weissmann et al., 2002; Knox, 2006; Bettis III et al., 2008; Mason, 2015). The impressive aggradation/progradation of the Alpine megafans was also prompted by the huge amount of sediment transported by Alpine glaciers to the valley mouths (Fontana et al., 2014). It has been demonstrated previously that high ratios of sediment supply to river discharge can drive net aggradation (Blum and Törnqvist, 2000). This is the case for the Alpine megafans during the LGM (Fontana et al., 2014). We know from previous studies (Lowe, 1992; Amorosi et al., 1996; Bruno et al., 2015) that aggradation also took place close to the Apennine margin. The smaller size of the Apennine alluvial fans (Fig. 2a) could be related to the smaller area and mean elevation of the Apennine river catchments (Fig. 2b), and to the fact that only restricted portions of the northern Apennines were covered by glaciers during the LGM (Giraudi, 2015).

After 18 cal ky BP, glacier melting in the Alpine region resulted in a dramatic increase in river discharge. At the same time, sediment load from the Alpine valleys was trapped within perialpine lakes formed in place of the former glacial tongues (Fontana et al., 2014). Thus, the ratio of sediment supply to water discharge was inverted and fluvial incision occurred in the Alpine sector of the plain. Increased sediment load

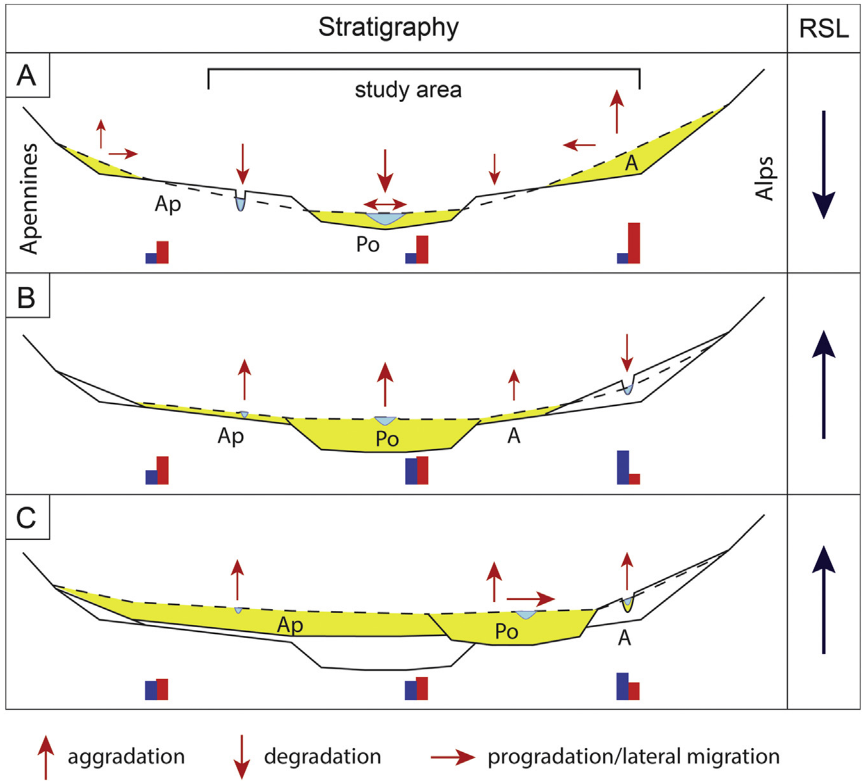

Fig. 11. Sedimentary response of Apennine (Ap), Alpine (A) and Po river systems to changes in sediment supply (red boxes), water discharge (blue boxes) and relative sea level (RSL) at the onset of the Last Glacial Maximum (A), during early deglaciation (B) and during the Holocene (C). Dashed lines represent hypothetical longitudinal profile of Po tributaries. Sediment deposited in each stage are represented in yellow.

generated by the erosion of Alpine megafans led to downstream aggradation (i.e., Po River aggradation, Fig. 11b).

The Holocene sediment succession records aggradation in the Po-Apennine sector and within the Alpine post-LGM valleys (Fig. 11c), although sediment supply was reduced by the widespread afforestation of river catchments (Vescovi et al., 2010). We argue that Holocene aggradation was mainly controlled by increased accommodation in response to the post-LGM sea-level rise (Bruno et al., 2017b). In particular, following Melt Water Pulse 1B, the Adriatic coastline migrated rapidly up to the maximum ingression line, which is located about 60 km east of the study area (Amorosi et al., 2017b; Bruno et al., 2017a). Geometric relationships between the LGM and Holocene Po channel belts (Figs. 6–9) also denote an overall northward migration of the Po River, with consequent cannibalization of the most distal portion of the Alpine megafans (Fig. 11c). Consistent with geomorphological and subsurface investigations (Burrato et al., 2003; GeoMol Team, 2015), we argue that the growth and northward migration of the buried Apenninic thrust-related folds may have contributed to the northward migration of the Po River. However, additional data are required to support this hypothesis (e.g., Late Pleistocene and Holocene slip rates of Apennine blind thrusts). The data available at present cannot be used to discern the relative importance of local tectonics and high-frequency climate changes in controlling sedimentary dynamics.

In general, the Late Pleistocene-Holocene stratigraphic architecture of the central Po Plain resulted from the interplay between global and local factors. Climate changes influenced (i) the balance between sediment supply and water discharge through glacier and vegetation dynamics, and (ii) the rate of sea-level fall/rise. Lithological and morphological (mean elevation, width) characteristics of river catchments, as well as river and valley gradients, determined the type of sedimentary response to external forcing (e.g., aggradation versus degradation).

7. Conclusion

The detailed reconstruction of subsurface stratigraphic architecture in the central Po Plain provides valuable information about the evolution of the Po River system during the last 30 ky. We summarize the main results of this research as follows:

1. Correlation along four stratigraphic panels from the Apennine to the Alpine margin revealed a consistent, tripartite zonation of the Late Pleistocene-Holocene stratigraphy. From south to north, these three zones were fed by Apennine, Po and Alpine river systems. The transition from Apennine to Po deposits is marked by the sharp boundary between a mud-prone, alluvial-plain (Apennine) depositional system and a thick (Po River) fluvial channel-belt sand body. In contrast, the boundary between Po and Alpine deposits, corresponding to a fluvial scarp at the surface, has no clear lithologic expression in the subsurface. It was traced as an erosional contact within seemingly homogeneous sandy deposits based on compositional and chronological data.
2. Stratigraphic relations between Apennine, Alpine and Po sediment bodies testify to a complex series of depositional and erosional events that occurred in the last 30 ky BP. A decoupled sedimentary response of Alpine and Po River systems to climate change is recorded at the onset of, and after, the LGM. At the onset of the LGM, Po incision and aggradation of Alpine rivers affected the central Po Plain. Soon after the LGM, the Po River aggraded onto the former floodplain, whereas Alpine rivers entrenched in narrow valleys. The Holocene stratigraphy records the overall aggradation and northward migration of the Po River, with consequent erosion of the distal portion of the Alpine megafans.
3. The combined effect of global and local factors controlled the depositional architecture of the central Po Plain. Apennine, Alpine and Po

river systems responded in distinct ways to external forcing due to the different characteristics of their catchments and longitudinal profiles. The Alps, with peaks over 4000 m, were glaciated largely during the LGM, whereas glaciations did not significantly affect the northern Apennines where the highest peaks are <2200 m. Exceptionally high rates of sea-level fall induced Po River incision at the onset of the LGM. Contemporaneous aggradation close to the Alpine chains was favored by (i) the gradient of the Alpine tributaries, greater than the gradient of the Po Plain and (ii) the huge amount of sediment transported from the Alpine glaciers to the valley mouths, feeding the related fluvioglacial systems (high sediment supply to water discharge ratio). At the beginning of deglaciation, Alpine rivers experienced channel entrenchment in response to (i) high water discharge due to the glaciers melting and (ii) sediment trapping from perialpine lakes, which formed at the Alpine margin in place of former glacial tongues (i.e., low sediment supply to water discharge ratio).

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